

Can We Better Address the Siting of Hazard Division 1.3 Systems

J. Covino
Policy Development Division
Department of Defense Explosives Safety Board
Alexandria, Virginia

T. L. Boggs
Jacobs Technology Naval Systems Group
Ridgecrest, California

ABSTRACT

The United States (U.S.) Department of Defense Explosives Safety Board (DDESB) is responsible for siting ammunition and explosives (AE) for Department of Defense (DoD) storage and transport worldwide in times of peace and war. All siting requirements are outlined in DoD 6055.09-STD, "DoD Ammunition and Explosives Safety Standards" (Reference 1). Current methodologies for siting AE allow mixed storage of Hazard Division (HD) 1.1, 1.2.X, 1.3, 1.4, and 1.6 and follow the equation:

$$D = k(\text{Net Explosive Weight})^{1/3}$$

Generally, if a storage site or an operating building is sited for HD1.1, the only limitation for HD1.3 AE storage is the physical capacity of the facility. However, HD1.3 systems pose a mass fire hazard and are uniquely different when compared to detonable systems (HD1.1).

This paper discusses the following:

- Many of the recorded accidents have been caused by fire.
- The false impression that HD1.3 materials are safer than HD1.1. For example, HD1.3 material is much easier to ignite than HD1.1. In addition, HD1.3 readily burns at atmospheric pressure, whereas HD1.1 material generally does not.
- Mixed storage of HD1.3 with HD1.1 may increase the probability of accident.
- While HD1.3 materials do not project hazardous fragments, burning HD1.3 materials in buildings with heavy confinement can cause catastrophic failure of the structure with projection of lethal fragments.
- Why $D = kW^{1/3}$ is inappropriate for determining safe separation distances for mass burning events and may result in excessive safe separation distance requirements.

This paper presents a recommendation for an alternate method for determining safe separation distances from mass fire accidents based on human response to fires and radiation from the fires. It is based on preventing second-degree burns caused by heat flux and exposure time. The paper also suggests that in some instances separate storage of HD1.3 may be a safer alternative.

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INTRODUCTION

This paper is the second part of a two paper effort. The first paper, Reference 2, presented a portion of a DDESB Technical Publication (not yet published) and focused on accidents, incidents, and testing. This paper takes the lessons learned presented in Reference 2 and makes recommendations for DDESB consideration. Some of the lessons learned include:

- Fires were often the first major reaction in many of the accidents.
- The fires often burned for minutes and even hours before the next significant reaction.
- Mass fire can transition to mass explosion/mass detonation. The next significant reaction following fire was often explosion(s) that in turn was sometimes followed by detonation.
- While in many of the accidents the fire burned for significant time, in some instances explosions occurred very quickly. For example, in test 4 (discussed in Reference 3), fire resulted in over-pressure and rupture of an earth-covered magazine in one second after ignition of the gun propellant. This was not a detonation, there was no blast over-pressure and no crater was formed, but five huge fragments were produced and thrown significant distance. This was caused by burning of HD1.3 material.
- The Milan 2004 accidents described in Reference 2 also produced huge fragments that traveled great distances (outside the Inhabited Building Distance (IBD) arcs).
- One of the major determinants in whether or not burning leads to significant debris being thrown great distances is the race between pressurization due to combustion versus the venting of reaction products from the confining chamber. Of critical importance is whether the flow through the vent(s) was either unchoked or choked. Choked flow occurs when the pressure inside the chamber is approximately 1.7 to 1.9 times the outside pressure.
- If the flow was unchoked, unburned energetic material was expelled and burned outside the chamber not inside the chamber.
 - Reports on some of the accidents reported plumes extending several hundred feet outside the chamber after the magazine doors, or headwall, were blown open.
 - The tests also showed plumes out a significant distance from the chamber. When the plumes from 1/10th scale test were scaled by analysis to full-scale, the calculated plume was out 250 feet.
 - There was significant heat flux associated with the plumes.
- In contrast, choked flow can rapidly lead to pressurization and rupture of the confining structure and spreading of secondary fragments/debris as presented in Reference 2.

These are just some of the lessons learned presented in Reference 2. Some additional lessons learned will be presented in discussions in the following sections.

Before those discussions, it should be mentioned that HD1.3 is a large class of varied materials ranging from gun propellant grains to large rocket motors to flares. Each of these varied materials have different compositions, thermochemistry, burning rates, burning surface areas, and combustion products leading to different pressurization rates in confinement. References 4 and 5 discuss these differences.

DISCUSSION

There is sometimes a disconnect between assignment of Hazard Division and the hazard, and the resulting determination of safe separation distances associated with burning of energetic material.

In the U.S., the process leading to assignment of a hazard division classification is described in TB 700-2 (Reference 6). This is based largely on United Nations (UN) Series 6 tests. A major deficiency in the process is that it does not consider the role of confinement and venting of storage structures. Materials classified as HD1.3 stored in heavy confinement with insufficient venting can when burning cause catastrophic rupture of the confinement and throw debris significant distances, as attested by lessons learned from accidents and testing that was reported in Reference 2. The CHAF effort (described in Reference 7 and presented in the larger DDESB Technical Paper, in preparation, but not reported in Reference 1 because the energetic materials were commercial fireworks) provided excellent examples of how the assignment of Hazard Division based on the UN Series 6 tests did not sufficiently predict the hazard effects of the commercial fireworks stored in International Standards Organization (ISO) containers. Some of the commercial fireworks that were classified as HD1.1 in the UN tests displayed mass fire behavior when ignited in the ISO container, while some of the items classified as HD1.3 displayed mass explosion behavior in the ISO container tests.

CURRENT WEIGHT BASED SITING METHODS FOR MASS FIRE HD1.3 NEED TO BE REVISED

Current safe separation distances for HD1.3 are presented in DoD 6055.09-STD (Reference 1). They, like quantity-distance for HD1.1, are closely based on the weight of energetic material using the simple equation:

$$D = kW^{1/3}$$

where:

- D = safe separation distance, or quantity-distance arc
- k = factor as defined in Reference 1
- W = weight of energetic material

In fact, the simple formula is applied exactly, for HD 1.3 explosives weights 1,000,000 lbs (454,000 kg).

There are two k factors for HD1.3: one for IBD and Public Traffic Route Distance (PTRD), and one for Intraline Distance (ILD) and Intermagaine Distance (IMD). In comparison, there are many k factors for HD1.1.

- The current weight-based siting methods are appropriate for mechanical shock initiation of HD1.1 but are not really appropriate for HD1.3 for several reasons. One reason is there are very different initiation methods, time scales, and resultant hazards. These are shown in Table 1.

TABLE 1. Fundamental Differences Between HD1.1 and 1.3.

Consideration	Mass Detonation/Mass Explosion	Mass Fire
Input stimuli	Fire or shock wave	Ignition
Initiation time	Microseconds after shock	Up to several minutes
Event time	Milliseconds to seconds	Minutes to several minutes to hours
Stores/time participation	Almost all react simultaneously	Time delays, some un-reacted
Reaction output	Blast and fragments secondary debris	Fireball and radiation, throw if choked flow
Cause of fatalities	Crush, dismemberment, fragment penetration	Second- and third-degree burns

- For HD1.1, the weight-based approach is applicable because the reaction times are very quick, as are the event times, and almost all of the explosive mass is rapidly and almost simultaneously consumed. In contrast, for HD1.3 the initiation and reaction times are spread over minutes to tens of minutes, and all of the mass is not reacting simultaneously. In some causes, some of the mass may not react at all. In a detonation or explosion, the reaction from unreacted solid to reacted gaseous products can almost be represented by a step function in time (and is often modeled simply as a discontinuity) while the ignition and combustion are very time dependent.
- Fires may have burned for some time, so part of the original weight has been consumed.

What are the hazards associated with HD1.3 systems? The principal concerns are as follows:

- Direct contact with exhaust plumes or fireballs. The exhaust temperatures of rocket motors are in the range of 2,000 to 2,300°C. Obviously, structures and walls can channel the flow of plumes. Exhaust plumes rapidly expand with temperatures over 1,000K and in some instances to distances of 200+ meters (m) from the source. The accidents and tests described in Reference 2 mentioned plumes out to 250 feet or more. Direct exposure to these temperatures will result in fatalities.
- These hot gases and, in the case of some solid missile propellant exhausts, hot metal oxides (such as Al_2O_3) can radiate to distance, providing radiation heat fluxes in the kW/m^2 range out to 400 m from the reactions.

In addition to these principal concerns, the following also need to be considered:

- If there is not sufficient venting of the hot combustion gases, pressure can build up and cause catastrophic rupture of the building and produce debris fragments. Again, the accidents and tests described in Reference 2 clearly showed this. HD1.3 systems are considered to be HD1.1 (for Quantity distance [QD]) when stored in underground chambers.
- If the HD1.3 stores are rocket motors, inadvertent ignition can cause the motors to go propulsive and spread burning reactions. Again, the exhaust plumes are in the 2,000 to 2,300°C range and can cause sympathetic ignition of adjacent stores.

The current weight-based method for siting mass fire is not based on the following:

- Human health risks/consequences based on direct exposure to flame or to radiative heat flux-exposure time relationships.
- Consideration of time dependent heat flux based on what is actually burning at any given time.
- Consideration of confinement in determining what is actually burning. The confinement can be provided by motor casings, shipping containers, and the building itself.
- Consideration of venting to prevent pressure build-up.
- Consideration of propulsive reactions and subsequent consequences.

Given that the fatalities associated with HD1.3 materials are largely caused by direct exposure to fire and radiative heat flux, determination of safe separation distance for HD1.3 should reflect the above considerations. Due to the above reasons, treating HD1.3 siting using a weight-based methodology is not an appropriate approach, and may not always provide adequate protection.

Other considerations for mass fire include:

- Ignition sequence—what is burning at what times, which in turn is determined by:
 - The energetic materials.
 - The stimulus.
 - The environment, including confinement.
- The heat flux produced as a function of time.
- Heat flux roughly diminishes with distance ($1/d_2$) and obstacles can provide shielding.

Concerns about of the current weight-based approach have been advanced by others in previous DDESB seminars and other documents. Tinkler (Reference 8) stated that:

“In the writer’s opinion this concept of relating the radius for a certain degree of (acceptable) hazard to the explosive quantity by a simple mathematical relationship is justified only when blast is the predominating effect producing the hazard. This implies that it is essentially wrong in principle for other than HD1.1 mass exploding explosives.” and

“In contrast with the blast and projection effects of HD1.1 and HD1.2 explosives, the fire behaviour of HD1.3 explosives has hardly been studied at all. This is in spite of the large quantities of propellants which are used, particularly in military ammunition.”

Tinkler (Reference 8) also reported on tests conducted in the United Kingdom (UK) in the 1970s and mentioned “a roaring flame jet swept for 200 feet (60 meters) horizontally along the ground” after discharging from the open end of the room. This is similar to the fireballs described in Phases II and III of the DDESB funded program described in References 9 and 10. Tinkler concluded:

“Consideration of some HD1.3 quantity distances show many anomalies and imply that the level of protection they afford may be inadequate compared to HE1.1 and 1.2 explosives whose effects are better understood. It is the strongly held view of the writer that the behaviour in a fire of boxed propellants, and the various types of rocket motor classified as HD1.3, does not lend itself to theoretical study nor modeling. Large scale test firings should therefore be carried out to confirm, or otherwise, the presently accepted quantity distances. More

immediately, large quantity HD1.3 storage facilities should be surveyed to ensure any probable jetting effects from buildings do not produce an unacceptable communication hazard.”

Crockart (Reference 11) also championed the need for a heat flux based approach for HD1.3 mass fires and for programs to address this need, as stated below:

“A careful review of the causes of death and injury in 81 accidents in the explosives and propellant industries over the 1959-1968 period, reported in Reference A, showed that primary blast (over-pressure) damage did not cause a single death but projected fragments and the effects of exposure to the searing radiant heat accounted for 77 of the 78 fatalities covered by the review. The great majority of these accidents involved a fire that eventually lead to a mass detonation.

Although there have been studies undertaken over recent years to understand the hazard mechanism and devise more effective protection for blast and projected fragment injury, the subject of protection from radiant heat has not been well studied.”

The Statement of Work for the DDESB program from the late 1970s and 1980s (References, 9, 10, and 12) included:

“A program of research and testing has been undertaken to correct the deficiencies in the safety standards for articles and substances of Class 1, Divisions 3 and 4.”

Some of the deficiencies listed included:

“It has been observed that, while cube-root scaling [of the weight of explosive material] applies to the blast over-pressures from explosions, thermal radiation incident on a surface exposed to a burning source does not scale in this manner. Furthermore, source parameters other than the total weight of combustible material present, such as geometry, affect the irradiance from the source. [Italics added in this paper for emphasis.]

IF THE CURRENT WEIGHT-BASED APPROACH IS INAPPROPRIATE, THEN WHAT APPROACH SHOULD BE USED TO DETERMINE SAFE SEPARATION DISTANCES FOR HD1.3?

Any other method should reflect that the risks from mass fires result from direct exposure to plumes (almost certain death) and exposure to thermal radiation. As mentioned above, the plumes associated with unchoked flow can carry hundreds of feet from the magazine. Reference 1 presents an equation to estimate the diameter of fireballs associated with HD1.3:

$$D_{\text{fire}} = 10 W_{\text{EFF}}^{1/3}$$

where:

D_{fire} = diameter of the fireball (feet)

W_{EFF} = 1.2 times the weight of HD1.3 material involved (pounds)

Table 2 presents the fireball diameter calculated for various weights of HD1.3 using the above equation.

TABLE 2. Fireball Diameter Calculations.

Weight, lb	Calculated Fireball Diameter, ft
10,000	229
100,000	493
250,000	669
500,000	843

For example, siting a facility for 100 pounds HD1.1 (QD - IBD 658 feet; PTRD 375 feet; ILD 84 feet) would allow siting of 500,000 pounds of HD1.3 (QD - 569 feet; IBD/PTRD; 372 ILD) without any restrictions. However, as seen in Table 2, the fireball diameter is calculated to be 843 feet and not considered in the siting limitations.

Furthermore, the calculated fireball radii extend almost as far as the IBD and PTRD distances and exceed the ILD distances for the given weight of HD1.3 material (Table C9.T13 of Reference 1).

Even if personnel are further away from the plume, the effect of radiant heat flux still must be considered. Some DDESB documents (e.g., DoD 6055.09-STD (Reference 1), sections C4.3.1.2 and C4.4.5) present a heat flux of 0.3 cal/cm²sec (12.56 kW/m²) as a limiting factor but does not present an exposure time. A heat flux of 12.56 kW/m² only gives an exposure time of a few seconds before second-degree burns, with the concomitant possibility of fatalities, would ensue. When Reference 1 does present both heat flux and exposure time (C4.3.2.4), it links the two by the equation

$$Q = 0.62t^{-0.7423}$$

where:

Q = heat flux (cal/cm²sec)

T = exposure time (seconds)

Use of this equation would give t = 2.66 seconds for a heat flux of 0.3 cal/cm²sec, and t = 8.9 seconds for a heat flux of 0.122 cal/cm²sec (5 kW/m²).

Other studies with DDESB involvement have used the Society of Fire Protection Engineers (SFPE) recommendation for heat flux-exposure time (with a 1.5 factor of safety applied to reduce the exposure time). This relationship is plotted in Figure 1.

It is recommended that DDESB adopt the prevention of second-degree burns as a criterion for determining safe separation distances from mass fires, and revise DoD 6055.09-STD (Reference 1), sections C4.3.1.2, C4.3.2.4, and C4.4.5, to use both heat flux and exposure time, and use the SFPE plot and equation presented in Figure 1.

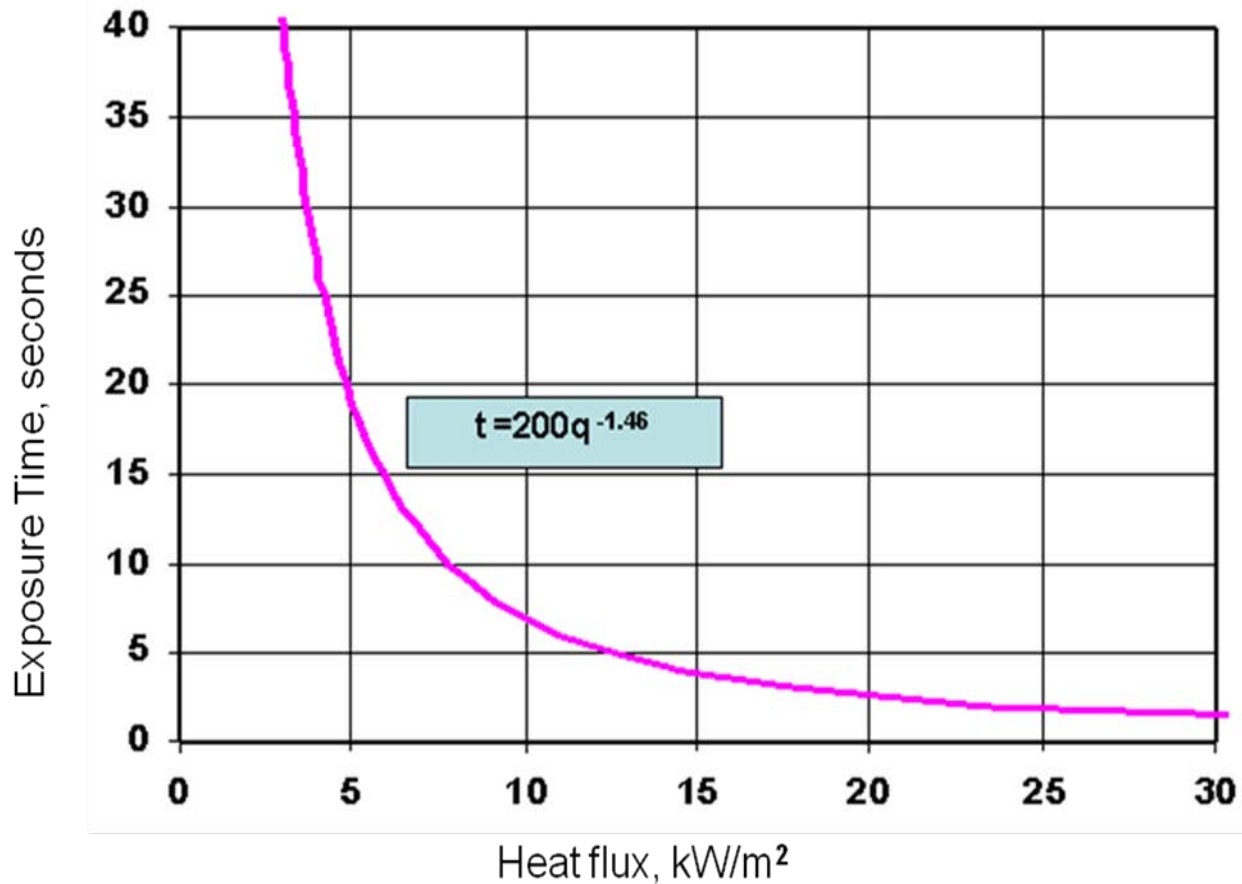


FIGURE 1. Heat Flux and Exposure Times for Onset of Second-degree Burns.

HOW DOES THIS COMPARE WITH OTHER INDUSTRIES?

The liquefied natural gas (LNG) industry has studied heat fluxes produced by accidental fires and explosions of LNG on land and water and are governed by federal and industry regulations. References 13 through 15 present summaries of these regulations and code, and some of the work is summarized as follows. The National Fire Protection Association's LNG Standard NFPA 59A (2006) (Reference 16) lists various thermal radiation fluxes for different exposure conditions. These include (from Reference 15):

- 5 kW/m² for persons at the proposed fence line of the facility or for the nearest point where groups of 50 or more people are in an outdoor assembly area outside the fence line.
- 9 kW/m² for the nearest point of building used for assembly, education, health care, detention and correction, or residential occupancy for a fire in an impounding area.
- 30 kW/m² for a property line that can be built upon over an impounding area.

The U.S. Department of Transportation's regulation 49, CFR 193 (Reference 17), also specifies the 5 kW/m² thermal radiation exposure at the LNG facility fence line and for groups of 50 or more people outside the fence line.

In addition, there is a European standard for the installation and equipment for LNG (Reference 18). This standard gives three flux levels: 13 kW/m² for persons at a fence line in a remote area, 5 kW/m² for persons at a fence line in an urban area, and 1.5 kW/m² for plant personnel who must remain in an unshielded area without protective clothing or an urban area with more than 20 people per square kilometer or a place difficult or dangerous to evacuate on short notice (e.g., hospital, retirement home, sports stadium, school). Similarly the Canadian Standards Association uses the 5 kW/m² criterion for persons at the fence line and for groups of 50 or more outside the proposed fence line (Reference 19).

While the above give the acceptable radiation heat flux, they do not specify the duration of acceptable exposure. However, some of the documents indicate approximately 30 seconds of exposure time before fatalities would occur and imply that within that time interval personnel should be able to find shelter; however, mention is made of susceptible groups such as young children and the elderly who are perhaps not as ambulatory as the rest of the population.

As pointed out in Reference 20, the 5 kW/m² limiting criterion does not adequately represent the risks presented by an LNG facility to sensitive populations like young children or the elderly and/or critical areas and buildings. They mention that the most widely recognized and used methods for establishing the impact of thermal radiation on people are those developed by TNO and published in the Green Book (Reference 21). These methods are referred to as thermal radiation probits or vulnerability models.

A probit (probability unit, Y) is a normally distributed random variable with a mean of 5 and a standard deviation of 1. The mortality response (percent fatality) is expressed as:

$$P = 1/2 + 1/2 \operatorname{erf} \{ (Y-5)/1.414 \} \quad (1)$$

Probit analysis can also be applied to thermal radiation hazards by

$$Y = A + B \ln(tI^{4/3}) \quad (2)$$

where:

A and B are probit parameters established from measurements and/or critically evaluated scientific data

I = the radiation intensity in W/m²

t = exposure time in seconds

The TNO Green Book (Reference 21) gives the probits for first- and second-degree burns, fatality for persons unprotected by clothing, and fatality protected by clothing. For example, the probit in the form of Equation (2) for second-degree burns is A = -43.14 and B = 3.02. The probit values from the Green Book (Reference 21) are used to generate a plot of incident heat flux versus exposure times leading to a 1% probability of injury (first- or second-degree burns) or fatality. From Figure 3 of Reference 20, the following exposure times would occur for an incident heat flux of 5 kW/m²

- First-degree burns would occur in approximately 14 seconds exposure time.
- Second-degree burns would occur in approximately 45 seconds.
- A 1% chance of fatality without proper clothing would occur in approximately 50 seconds.
- A 1% chance of fatality with proper clothing would occur in approximately 70 seconds.

The above discussion has been for the LNG industry. The petroleum refining industry has also considered radiation heat flux, primarily from “flaring” operations for safe disposal of flammable waste gases. Various flux levels are specified in the American Petroleum Institute standard API 521 (Reference 22). These include (1) 15.97 kW/m² for heat flux on structures where operators are not likely to be performing duties and where shelters from radiant heat is available, (2) 9.46 kW/m² for any location where people have access (but exposure should be limited to a few seconds), (3) 6.31 kW/m² for areas where emergency actions lasting up to 1 minute may be required by personnel without shielding but with appropriate clothing, (4) 4.73 kW/m² for areas where emergency actions lasting several minutes may be required by personnel without shielding but with appropriate clothing, and (5) 1.58 kW/m² for any locations where personnel with appropriate clothing may be continuously exposed to design flare release conditions.

Reference 23 presents the results of a worst-case consequence analysis for process unit modifications and additions to BP Carson (CA) Refinery. They considered flash fire hazards, radiation hazards, overpressure hazard, and toxic products hazards. For the radiation hazard analysis, they used the 5 kW/m² level, noting “When people see a fire, it is easy for them to determine which direction they should move to increase the distance between them and the fire and thus lower the impact of the fire on them, or they can find a building or other solid structure to go behind to reduce or eliminate the radiant impact. If a person is already inside a building, they will be protected from the radiant impact. [This radiant level is not high enough to ignite a building.]”

IN ORDER TO PREVENT MASS FIRE TRANSITIONING TO MASS EXPLOSION/DETONATION, CHOKED FLOW MUST BE PREVENTED

Reference 24, also made the argument: “... the effects of burning HD1.3 material inside a closed structure can range from benign to catastrophic. If adequate venting is not provided, the pressure can build up at such a rapid rate that it can overwhelm the structure. This explains why it is safest to store HD1.3 materials in structures that provide large amounts of venting. [emphasis added] In above-ground structures this venting is provided through frangible walls and/or roofs. When HD1.3 materials are stored in hardened structures or any other structure that provides structural confinement, extra care should be taken to provide adequate venting. The amount of venting required varies with the volume of the storage chamber, the weight of the [energetic] material being stored, and its [mass] burn rate. [Note: In addition to the weight of energetic material, its thermochemistry/energy content is also an important consideration. We inserted mass into burning rate above because the term burning rate is often construed to mean surface regression rate while mass burning rate, which is an important determinant of the pressure-time history of the event, considers not only the surface regression rate but also burning area and density.] These phenomena are not adequately addressed in the current versions of the explosive safety standards—either from the standpoint of safe separation distance or asset protection.”

These words from 1996 are just as true today as they were in 1996.

MIXED STORAGE OF HD1.1, 1.2, AND 1.3

Reference 5 presents the differences in ignitability and burn rates for HD1.1 and 1.3 energetic materials, with HD1.3 propellants being easier to ignite and burning well at one atmosphere, whereas many HD1.1 materials burn poorly at one atmosphere. When storing HD1.1 and 1.3 together in the same facility or structure, problems may be encountered because the HD1.3 materials may serve as the “match” that start the mass fires that may, or may not, transit to mass explosion/detonation. There is the desire to have robust storage such as earth-covered magazines to protect HD1.1 from incoming blast and fragments because of the detonability of HD1.1 materials, but perhaps separate frangible storage for 1.3 materials is also desirable.

As mentioned previously from Reference 24 and in Reference 2, burning of HD1.3 in a choked flow situation can easily result in rupture of heavy confinement very quickly (in one instance, 1 second after ignition) with debris thrown to great distances, especially if the rupture is very quickly followed by a detonation.

One suggested possibility is to store HD1.3 in buildings having frangible blow-out panels in the roof and selected walls to ensure that choked flow does not occur and to direct the flame/plume into desired directions.

The issue of mixed storage may become more acute in the future given the emphasis of Insensitive Munitions programs to move from inadvertent detonation and explosions reactions to fire-type reactions.

HAZARD DIVISION 1.3 PROPOSED CHANGES IMPACTS ON DDESB MODELS

Since, in general, HD1.3 substances ignite easier and burn better than HD1.1 substances at atmospheric condition, and since fire is the first major reaction in many of the accidents, the probability of an inadvertent accident is greater for HD1.3 systems than when compared to HD1.1. These phenomenological differences are not well captured in risk-based tools such as the DDESB Safety Assessment for Explosives Risk (SAFER) (Reference 25) except for the fact that Compatibility Group (CG) C is given a higher probability of event with respect to CG D (HD 1.1); most HD1.3 systems are assigned CG C. Risk assessment models are often based on HD1.1 because it has the higher consequence. However, actual siting allows mixed storage and therefore the higher probability of event associated with HD 1.3 may be neglected. In most risk assessment methodologies, the probability of event is generally not modified based on the probability of accident for one hazard division relative to another. Currently, in *STIKE-QRA* (Reference 26) a lightning risk assessment model under development for the DDESB, the probability of an event is not modified based on Hazard Division.

Another software tool developed by the DDESB, Automated Safety Assessment Protocol – Explosives (ASAP-X) (Reference 27) is an automated consequence model based on consequences given in DoD 6055.09-STD, it therefore, does not address probability of event.

RECOMMENDED NEW TESTS AND MODELING

As mentioned by several others, there is a need to have tests where fire is the initial stimulus with flame spread to adjacent stores. As mentioned earlier, HD1.3 encompasses many very different materials. So far, there has been little, if any, testing with rocket motors other than 2.75-inch rocket motors that were open at both ends. Tests with different configuration of materials are also needed. The configuration, as well as the material type, is important in determining unchoked versus choked flow, and in determining plume extent, fluxes, and reaction durations. Packaging also needs to be considered. Some studies showed that even cardboard containers can play a key role. One study recommended metal boxes that remain airtight to 100 kPa can play a key role for safely storing gun propellants. Other packaging options ought to be explored. Different configurations of surrounding confinement, for example frangible construction versus robust confinement like an earth-covered reinforced concrete structure, should be investigated. All tests should be well instrumented, especially to determine intense plume location and heat flux from the plumes.

Modeling efforts should be used in designing tests as well as interpreting the results. For example, what happens when choked flow results in extreme pressure buildup in an earth-covered magazine that in turn causes rupture of the structure, and what might happen if immediately following the rupture detonation of the remaining energetic material occurred? How might the detonation accelerate the large pieces of debris that had just been formed by the over-pressure driven rupture?

SUMMARY AND CONCLUSIONS

1. This document is a companion paper to Reference 2 and builds on the lessons learned as presented in Reference 2.
2. There is a disconnect between assignment of hazard division and determination of safe separation distances for HD1.3. Mass fires (HD1.3) may, or may not, transition to mass explosions/detonations (HD1.1).
3. The current weight-based methods for determining quantity-distance are not appropriate for determining safe separation distances for HD1.3, and may not always provide adequate protection. This was the conclusion of other authors as well.
4. A new method for determining safe separation distances from fires is needed, one that is based on risk and consequence. It is recommended that prevention of second-degree burns serve as the criterion and that the plot of heat flux-exposure time presented by the SFPE (Figure 1) be adopted.
5. It is recommended that HD 1.3 criteria in DoD 6055.09-STD (Reference 1), sections C4.3.1.2, C4.3.2.4, and C4.4.5, be revised. These revisions should also be incorporated in DDESB developed models and tools.
6. These changes would put the DDESB more in line with the practices of other industries where fire is a significant hazard.
7. It is imperative that choked flow be prevented in order to prevent rapid pressurization from burning reactions that can cause catastrophic rupture of containing structures and significant debris throw. Construction of buildings with frangible panels to allow proper venting to minimize choked flow should be considered for storage of HD1.3 materials.
8. Studies should be performed to determine the hazards of mixed storage of HD1.1, 1.2 and 1.3, given that HD1.3 materials are easier to ignite and burn more readily at one atmosphere than do HD1.1 materials—the HD1.3 provides the “match” that starts the fires and may lead to a transition from mass fire to mass explosion/detonation.
9. New tests and trials are proposed to study the hazards with fire as the initial stimulus.
10. Analytical models should be used to help design the tests and to help interpret the test results.

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Can We Better Address the Siting of HD 1.3 Systems



2010 DDESB Seminar

**Dr. Josephine Covino
Department of Defense Explosives Safety Board**

**Thomas Boggs
Jacobs Naval Systems Group**





Outline

- **Many accidents have been caused by fire**
- **False impression - HD 1.3 materials are safer than HD 1.1**
 - HD1.3 easier to ignite than HD1.1
 - HD 1.3 readily burns at atmospheric pressure,
 - Generally, HD1.1 does not burn well at atmospheric pressure.
- **Mixed storage of HD 1.3 with HD 1.1 may increase probability of accident**
- **HD 1.3 materials do not produce hazardous fragments**
 - HOWEVER, burning HD 1.3 materials in buildings with heavy confinement can cause catastrophic failure of the structure with projection of lethal debris fragments.
- **Why $D = kW^{1/3}$ is inappropriate for mass burning events**
 - Resulting in excessive safe separation distance requirements





- **This is the second paper of a two paper set**
- **The first paper presented a portion of a literature search that will be published as a DDESB Technical Publication**
- **This paper takes the lessons learned from the first effort and makes recommendations for future DDESB consideration**





HD 1.3

- **HD1.3 is a large class of varied materials ranging from**
 - Gun propellants that have large amount of surface area
 - Rocket motors that are designed to quickly achieve internal pressures ~1000 psia, and provide significant propulsive thrust
 - Flares that provide intense light output but not much gas
- **Significant differences in combustion rates and pressurization**





HD 1.3

As mentioned in previous presentation,

- **Consequence of burning HD1.3 depends on**

Pressurization due to combustion in confined volume

VS.

Venting of pressure from that volume

- **Very dependent on whether the flow is un-choked or choked**
- **Choking occurs when:**

$$p_{\text{inside}} / p_{\text{outside}} > 1.7 \text{ to } 1.9$$





Combustion of HD 1.3

- **Un-choked flow**

- Energetic material often expelled from structure and burns outside not inside
- Plume hundreds of feet outside

- **Choked flow**

- Pressure rapidly builds
- May cause rupture of structure
- Can occur in 1 second after ignition
- Can throw large pieces of structure debris considerable distances





Dis-connect between Risk and HD

- In US HD determined by TB 700-2 (largely based on UN Series 6 tests)
- Does consider role of case confinement but not structural confinement
- Materials with HD 1.3 can rupture heavy confinement and throw structural debris significant distances
- Probability of event for HD 1.3 is more probable when compared to HD 1.1 at atmospheric condition





CHAF Program

- **Concerned with fireworks but lessons may still be pertinent**
- **Some HD 1.1 by UN Series 6 underwent mild reaction in ISO containers, while**
- **Some HD 1.3 by UN Series 6 underwent mass explosion reaction in ISO containers**



Weight based QD inappropriate for HD 1.3



- **Weight based approach**
 - $D = kW^{1/3}$
- **Appropriate for mechanical shock initiation of HD 1.1 (mass explosion/detonation)**
- **BUT not for HD 1.3 (mass fire)**
- **Very different initiation, time scales and resultant hazards**





Mass explosion/detonation vs. mass fire

Consideration	Mass explosion/detonation	Mass fire
Input stimulus	Mechanical shock	Ignition
Initiation time	Microseconds after shock	Up to several minutes
Event time	Milliseconds to seconds	Minutes to several minutes to hours
Stores/time participation	Almost all react simultaneously	Time delays, some unreacted
Reaction output	Blast & fragments	Fireball/radiation, structural debris
Fatalities	Crush, dismemberment, fragment penetration	Burns, impact from structural debris



Hazards of mass fires

- **Plume**

- Rocket exhaust 2000-2300°C
- Plumes 1000°C out to 200+ meters in one study
- Un-choked flow 250 foot plumes

- **Radiation**

- Several kW/m² to 400 meters in one study
- Hot Al₂O₃ particles

- **Inadvertent propulsion**

- **Structural debris (choked flow)**



Current weight based siting for mass fire



IS NOT BASED ON:

- **Human health risk/consequences based on direct exposure to flames or to radiation**
- **Time dependent heat flux based on what actually burning at any given time**
- **Consideration of confinement in determining what is burning**
- **Consideration of venting to prevent pressure build-up**
- **Consideration of propulsion reactions and consequences**





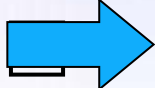
This is not a new concern

- **Pape, Waterman, and Takata, 1980**
- **Tinkler, 1982 DDESB Seminar**
- **Crockart, 1986 DDESB Seminar**
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- **Henderson, 2005**





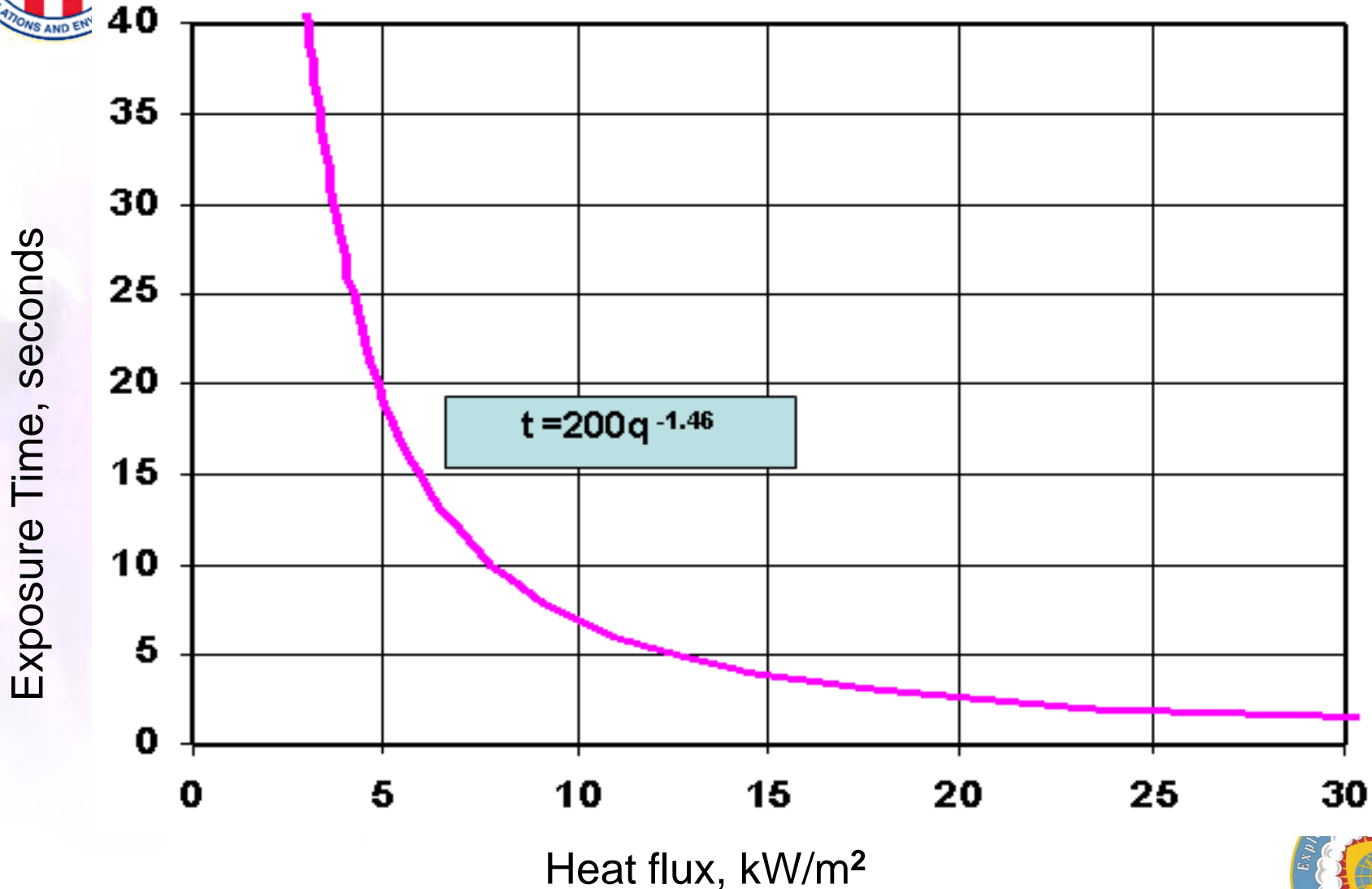
More appropriate safe separation from mass fire

- **Safe separation distance for mass fire should be based on fire plume locations and radiation**
 - Direct impingement of plume  fatalities
 - Fatalities due to radiation at distances due to radiation flux level and exposure duration
 - Prevention of second degree burns is realistic criterion for safe separation mapping
- **Prevention of structural debris from rupture**





Heat flux-exposure times for onset of 2nd degree burns





Heat flux in DoD 6055.09-STD

- **C4.3.1.2 and C4.4.5 presents a heat flux of 0.3 cal/cm² (12.56 kW/m²) as a limiting factor but no mention of exposure time**
- **Both heat flux and exposure time mentioned in C4.3.2.4 by**

$$Q = 0.62 t^{-0.7423}$$

- **Recommend changing DoD 6055.09-STD to conform to preventing 2nd degree burns and using SFPE equation as criterion.**



How does this compare to other Industries?



- **Liquified natural gas (LNG) industry - 5 kw/m² at fence-line, assumes enough time (20-30 sec) to take shelter to avoid 2nd degree burns**
- **US DOT 49 CFR 193 for LNG - 5 kw/m² at fence-line for LNG**
- **European standard for LNG - 5 kw/m² at fence-line in urban areas for LNG**
- **TNO Green Book probit analysis 2nd degree burns in ~45 seconds for 5 kw/m²**





Mixed Storage

- **Atwood paper at this meeting demonstrates that HD 1.3 materials are easier to ignite than HD 1.1 materials**
- **HD 1.3 materials burn well at 1 atm, while many HD 1.1 do not**
- **When HD 1.1 and 1.3 are stored together the HD 1.3 materials may serve as the “match” that start the mass fires that may, or may not, transition to mass explosion/mass detonation**
- **Combustion of HD 1.3 may cause rupture of structure and projection of debris if there is not sufficient venting**
 - **Must protect against choked flow**





Mixed Storage

- **It has been suggested that HD 1.3 materials should be stored by themselves in buildings of frangible construction**
- **Often that is not possible.**
- **Munitions often have a HD 1.3 motor but a HD 1.1 warhead**
- **Magazines have to be robust enough to withstand detonation reactions in adjacent magazines**
 - But, should also have sufficient initial venting, or frangible walls and/or roof that can vent at relatively low pressure
- **Insensitive Munitions programs trying to prevent detonations and explosions → burning**





Summary/Conclusions

- **Dis-connect between assignment of hazard division and determination of safe separation distance for HD 1.3.**
- **Mass fires may, or may not, transition to mass explosion/detonation.**
- **Current weight based approach for QD inadequate for determining safe separation distance for HD 1.3.**





Summary/Conclusions (cont)

- **Safe separation distance from mass fires should be based on risk and consequences.**
- **Recommend that prevention of 2nd degree burns and fatalities be criterion.**
- **Recommend use of SFPE heat flux-exposure time to prevent 2nd burns be used.**
- **Recommend DoD 6055.09-STD be changed to reflect this.**
- **This will put DoD in line with other industries.**





Summary/Conclusions (cont)

- **Imperative that choked flow be prevented**
- **Sufficient initial vent areas**
- **Frangible panels, walls, roof**
- **Mixed storage should be reviewed**
- **New tests involving fire as the initial stimulus should be performed**
- **Analytical models should be used to help design the tests and help interpret results**

